Development of Radiometric System Models for Performance Comparison of Proposed Instruments

Betina Pavri*, Greg Bearman, Jack Margolis, Philip Moynihan, and Karen Liu
Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 90041

ABSTRACT

Radiometric models have been used to optimize instrument design or evaluate impacts of changes to the design during integration and test. Tradeoffs such as spectral and spatial resolution, telescope and spectrometer temperature, aperture, f/No., integration time, optics and filter transmissions, and so forth can be quickly changed to evaluate changes to the signal/noise ratio or other performance metrics. An alternative use of such models is to identify promising instrument proposals for further study. A series of models were constructed to evaluate general instrument designs as an illustration of this process. These models included two grating spectrometers (whiskbroom and pushbroom) and a spatially modulated interferometer. All were given a common set of radiometric inputs and telescope optical prescription. Results of the modeling illustrate the performance differences between instrument types, although signal/noise predictions should be evaluated along with other parameters such as manufacturability, precision of calibration, and so forth. Such modeling allows instrument developers to demonstrate to potential customers improvements in their instruments, and the advantages of their product over other instruments for a specific application. If a common set of inputs is used for the different instrument models, this technique gives customers one metric with which to evaluate the disparate proposals.

Keywords: radiometric modeling, performance modeling, systems engineering

1. BACKGROUND

Two classes of passive, spectrographic instruments may be applied to the stand-off detection of chemical agents: hyperspectral and multispectral. Hyperspectral instruments include grating spectrometers and Fourier Transform Spectrometers (FTSs). Multispectral options include Acoustical Optical Tunable Filter (AOTF) instruments and Fabry-Perot (etalon) instruments, including Liquid Crystal Tunable Filter (LCTF) instruments. However, many recent AOTF and LCTF designs are now approaching hyperspectral resolution, so they may be technologies to watch. Fixed-filter systems would also fall in the multispectral category, but are not considered here as they are not easily modified (reprogrammed) during operation if this becomes necessary.

* Further author information -

B.P. (correspondence):	betina.e.pavri@jpl.nasa.gov	(818)354-6379
P.M.	philip.i.moynihan@jpl.nasa.gov	(818)354-4130

Multispectral systems can be simple and compact, but usually can not locate or identify subtle spectral features. The hyperspectral approach provides the necessary spectral resolution for the discrimination task, but instrument design is more complex and signal/noise in any channel will be lower, in general, because of the narrower spectral bandwidth. However, these systems have the advantage of flexibility, as they are not optimized for a specific set of bands. They can provide unique chemical identification and some atmospheric correction.

An advantage of grating spectrometers and some FTSs is that the spectra are collected simultaneously (while scanning spatially), hence removing concerns about spectral changes during the period of measurement from either the atmosphere, the target, or changes in the observation path length due to a moving platform. Michelson interferometer designs, which build up the transform of a spectrum by scanning through optical path difference, have this simultaneity concern, while a Sagnac interferometer design, which measures the entire transform of each pixel simultaneously, would not. Other issues may have a role in determining the choice of instrument; for example, if a wide swath is desired, AOTF and Fabry-Perot imagers might be eliminated from contention as these systems are not designed for off-axis imaging.

2. INSTRUMENT PERFORMANCE MODELING

The instrument configuration assumed for the models generated in this study is shown in Figure 1. To simplify this modeling effort, only the components from the optics through the focal plane were varied. The electronics, on-board processing, communications, and ground system processing were assumed to have only second-order effects and were held fixed.

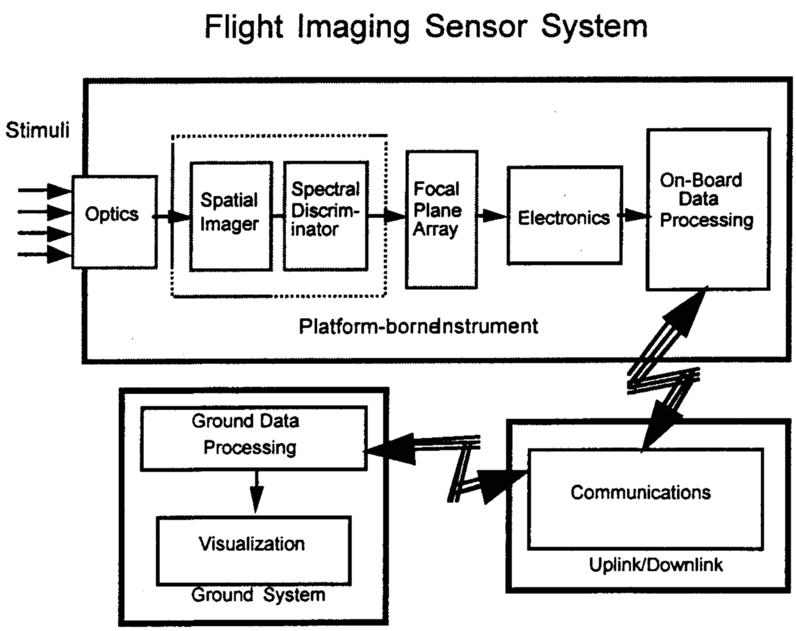

Figure 1. Schematic rendition of airborne (or other platform) instrument configuration

While many design options are available, for the purpose of this study four were chosen for further evaluation: two grating spectrometers (a whiskbroom and a pushbroom, the difference shown in Figure 2), and two FTS designs (a Sagnac and a Michelson).

The grating spectrometers both work by taking light from a ground pixel, and splitting it into a continuous spectrum using a grating. The radiance in each band is measured by a separate detector, and the entire spectrum can be read out. The whiskbroom design has a linear focal plane to measure the spectrum, but requires a scanner to image the swath. Pushbroom designs require a two-dimensional array (to measure the spectra of the entire swath simultaneously), but no scanner. The FTS instruments do not measure the spectrum directly. Instead, each builds up an interferogram from which the spectral information can be derived in post processing. The Michelson design uses a two-dimensional array to image an entire frame simultaneously, and a moving mirror to scan through the optical path difference (OPD) range to build up a spectral transform over the image. The Sagnac design also requires a two-dimensional array. Like the pushbroom spectrometer, it images one line at time, but the entire transform for each pixel within that line is collected simultaneously. In all four cases, the raw data will need to be corrected for atmospheric and instrument effects before a spectrum of the target will be available for analysis.

For this modeling, all four instruments were given a common set of radiometric inputs, telescope optical prescription, and instrument temperatures. It should be noted that this was done for the purposes of illustration and that these models represent a top-level description of the instrument; in an actual design, each instrument would be optimized to improve performance. The input radiance was produced using FASCODE and the HITRAN database, given spectral information on the gases of interest, and assuming a standard mid-latitude summer atmosphere.

whiskbroom/pushboom

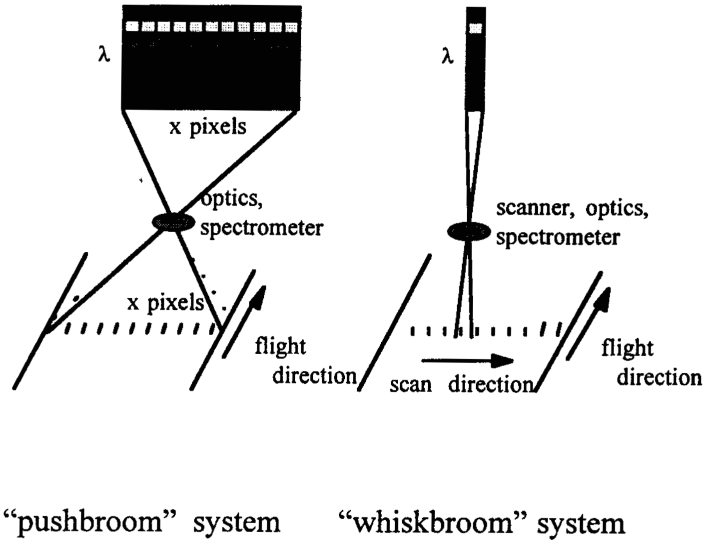

Figure 2. Configuration and operation differences of the "pushbroom" and "whiskbroom" grating spectrometer systems

The radiance received by the instrument was then degraded by the optical transmission/reflectances and grating/modulation efficiency. The photon flux due to instrument self emission was then estimated based on material emissivities, solid angle as viewed by the detector, and component temperature. This data can then be used to calculate the photon NEP at the focal plane.

$$NEP(\lambda) = \frac{hc}{\lambda} * \frac{1}{t_{int}} * \sqrt{\rho_{scene} + \rho_{instrument}}$$

where

$NEP(\lambda)$ = Noise equivalent power at a given wavelength
h = Planck's constant
c = Light speed
λ = Wavelength of interest
t_{int} = Integration time
ρ_{scene} = Photons from scene
$\rho_{instrument}$ = Photons due to instrument self-emission

The NEP at each λ is calculated over the bandwidth ($\Delta\lambda$) at that wavelength.

The signal/noise ratio for the instrument can be calculated as shown below. All photon contributions are converted to electrons based on the quantum efficiency of the detector. Finally, detector dark current and readout noise are included, based on typical values for commercially available HgCdTe focal planes.

$$S/N(\lambda) = \frac{e^-_{scene}}{\sqrt{(\text{rms } e^-_{readout})^2 + e^-_{dark} + e^-_{scene} + e^-_{instrument}}}$$

where

$S/N(\lambda)$ = Signal-to-noise ratio at a given wavelength
rms $e^-_{readout}$ = Readout noise electrons
e^-_{dark} = Dark current electrons
e^-_{scene} = Electrons contributed by the total scene
$e^-_{instrument}$ = Electrons contributed by the instrument

3. RESULTS

The signal-to-noise results are shown below in Figures 3 through 6. The signal-to-noise ratio was calculated separately for each system, and includes effects of etendue (throughput) and bandwidth.

All of the instrument designs benefit from instrument background flux-blocking filters. This reduces the number of photons reaching the detector that carry no information about the target, thus decreasing the shot component of the noise. For grating systems, a linear variable filter (LVF) can be used to further decrease background noise reaching each pixel. These filters can not be used with FTS systems, however, since FTSs do not measure the spectrum directly. In order to build up the spectral transform, all wavelengths of interest need to reach all the pixels in the focal plane.

Results of the modeling illustrate the performance differences between instrument types. Because of their long integration times relative to the whiskbroom instrument, the best performance in this study is derived from the pushbroom instruments (either the Sagnac FTS or grating spectrometer with LVF). For the Michelson FTS modeled here, no motion compensation was assumed, so its integration time is similar to that of the whiskbroom instrument. It was assumed that the optical path difference scan was completed within the time required for a half-pixel smear. More detailed modeling would be necessary to determine the effect of this smear on the spectral transform under a variety of observing conditions, though a real instrument would probably incorporate some sort of image motion compensation to eliminate it. This would mitigate the smearing problem, allowing a longer integration time and dramatically improving signal/noise.

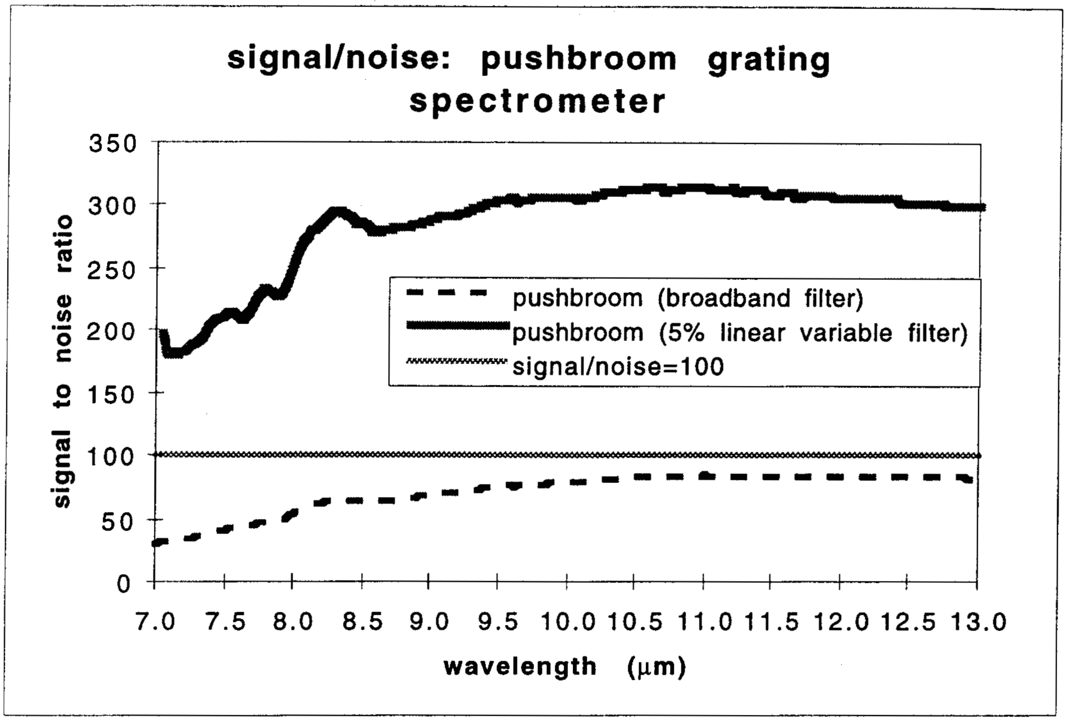

Figure 3. Signal-to-noise ratio at the focal plane array for a pushbroom grating spectrometer

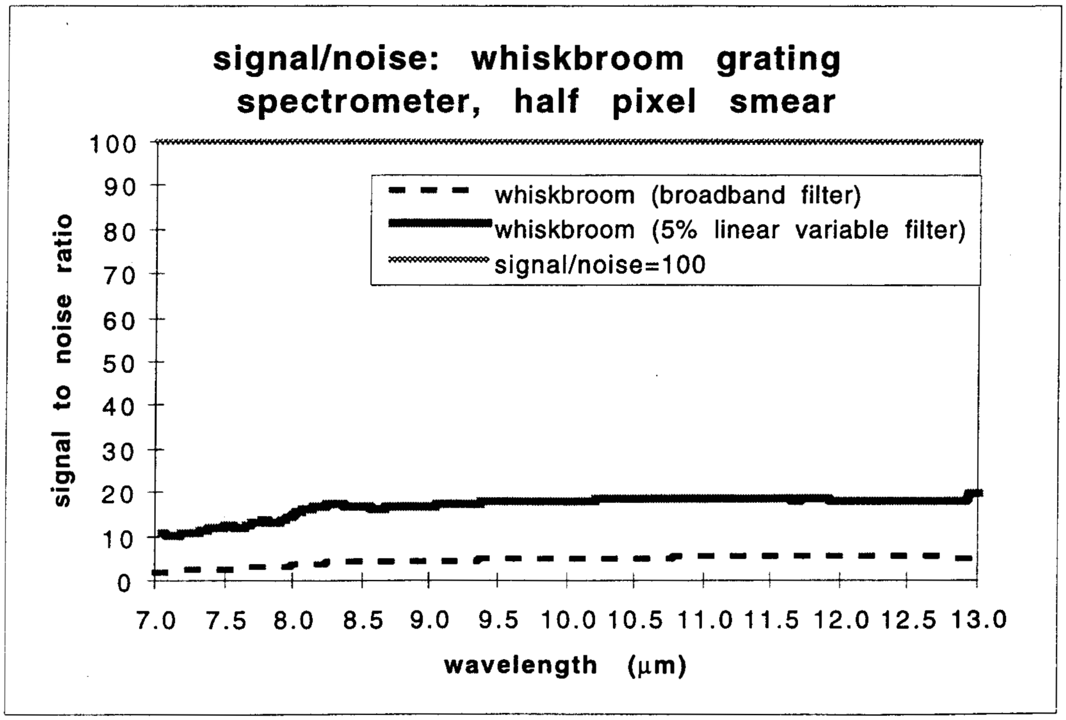

Figure 4. Signal-to-noise ratio at the focal plane array for a whiskbroom grating spectrometer

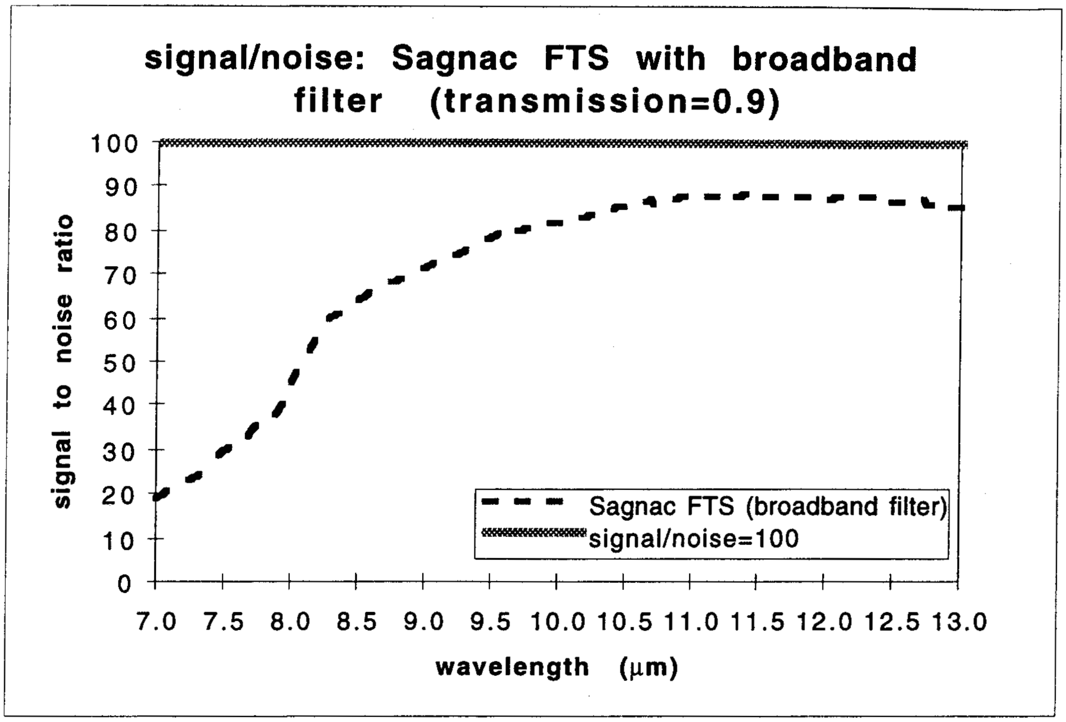

Figure 5. Signal-to-noise ratio at the focal plane array for a Sagnac FTS

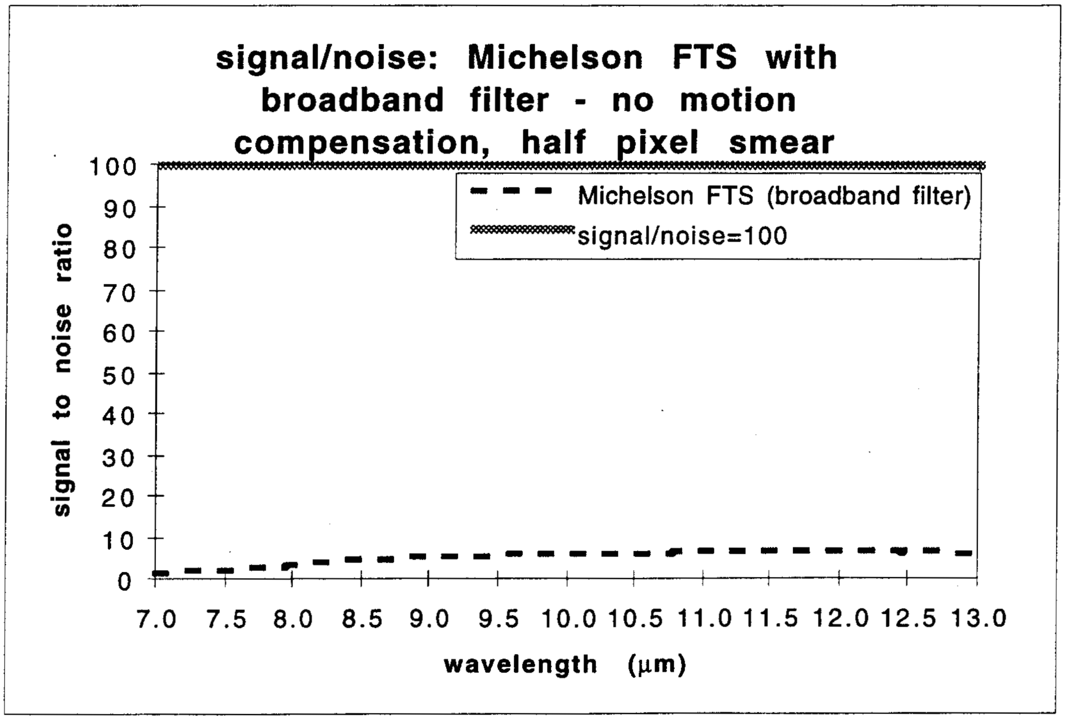

Figure 6. Signal-to-noise ratio at the facal plane array for a Michelson FTS

Signal-to-noise ratio and NEP are only two of many parameters one might use to quantify instrument performance. Other issues, such as the accuracy and precision of the calibration, will have a large role in determining whether the instrument can successfully detect its target. This may present designers with tradeoffs. For example, the pushbroom spectrometer has a superior signal-to-noise ratio to that of the whiskbroom spectrometer, but the whiskbroom spectrometer's radiometric and spectral calibration will be more precise because each ground pixel's spectrum is measured by the same set of detector pixels. On the other hand, FTS instruments do not require spectral calibration and are capable of greater spectral resolution than are the grating systems discussed here. However, uncompensated platform motion during data collection introduces errors into the spectrum derived from the transform in post-processing.

Finally, these results are specific to the non-optimized instruments modeled, and are not intended to represent the performance of instrument classes in general. As indicated earlier, the current models do not include signal processing effects. It should be noted that the signal-to-noise ratio is related to, but does not solely determine, the minimum detectable concentration (MDC) of the target substance. The MDC will be a function of the algorithms used to process the data, as well as observational conditions such as atmospheric conditions or variations in ground temperature/ emissivity in the field of view.

4. CONCLUSIONS

We recommend the development of radiometric performance models to locate proposed instruments in performance space. One example might be to compare instruments on a chart of minimum detectable level vs. spectral resolution as a function of noise equivalent spectral radiance (NESR). Customers evaluating these models should require them to use identical, standardized radiometric inputs, ensuring that they are all evaluated under the same conditions. We also recommend soliciting input from vendors on preferred input conditions. The purpose of this would be to gather feedback on whether one type of instrument performs better under one set of conditions, while another type would be preferable when tested against a different set of inputs.

A generalized signal chain for a model might look like Figure 7:

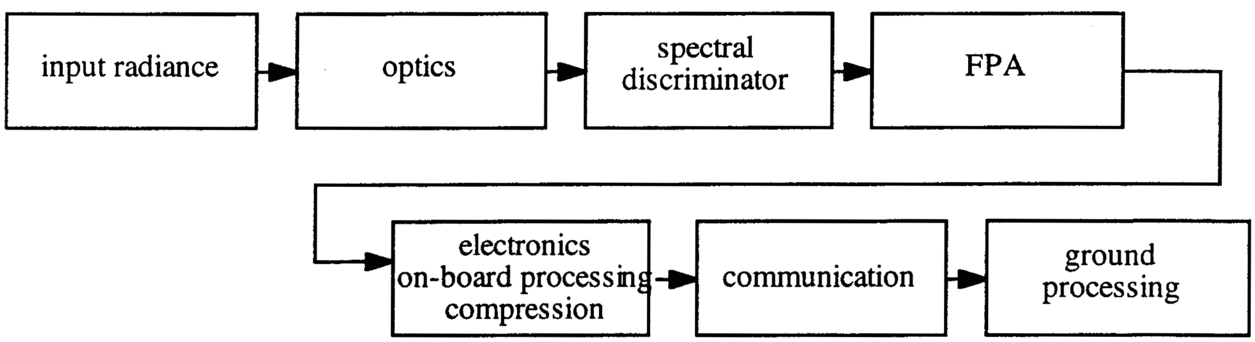

Figure 7. Generalized signal chain

The parameters associated with the components of the generalized signal chain, which should be addressed in the radiometric models, are presented in Table 1.

Table 1. Radiometric-model parameters for generalized signal chain

Signal Chain Component	Parameter
Input radiance	• Atmospheric/ground conditions (e.g., mid-latitude summer, 300K surface temp, ground emissivity, etc.) • Effect of emissivity/temperature variations across the scene: on the ground, in the atmosphere, and in the targeted gas cloud
Optics	• Optical transmission functions • Self emission (temperature and emissivity of optics) • etendue
Spectral discriminator	• Grating efficiency, prism transfer function, modulation efficiency • Spectrometer and dewar/coldshield self emission • spectral sampling and bandwidth
Focal plane array	• Pixel size • Quantum efficiency, detectivity, responsivity • Operating temperature • Dark current • Integration time
Electronics	• Contributions of various noise sources (digital-to-analog converters, etc.) • Discriminationalgorithms • Motion compensation, co-adding of samples, etc.

As a minimum, the radiometric models should simulate the signal chain at least through the electronics. The advantage of such modeling is that the instrument performance can be estimated and initial tradeoffs made before any hardware is built. Such modeling allows instrument developers to demonstrate to potential customers not only improvements in their instruments, but also the advantages of their product over other candidates for a specific application. If a common set of inputs is used for the different instrument models, then this technique would give customers one metric with which to evaluate disparate options.

5.ACKNOWLEDGEMENTS

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